Referring to the constituent 265, the chief term is 265·455, whose speed differs by $\dot{p}$ from the speed of 265·555; but there is no reason why the speed of the constituent 265 should be modified on this account, as any correction necessary would be automatically applied in using the variable coefficients and phases as indicated above.

To sum up, it is proposed—

(1) that the constituents be regarded as functions of τ, s, and h, with appropriate speeds;

(2) that analyses and predictions should be made with variable coefficients and phase corrections, automatically applied if possible, such coefficients and phase corrections being regarded as constants only over a sufficiently short interval of time.

The translation of these proposals into practical methods, however, is a matter for careful consideration.

The Production of Single Crystals of Aluminium and their Tensile Properties.

By H. C. H. Carpenter, F.R.S., Professor of Metallurgy, Royal School of Mines, and Constance F. Elam.

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[Plates 9–12.]

The crystals of which metals and alloys are composed are allotriomorphic. They are generally very small, and cannot usually be distinguished without the aid of a microscope. It is quite true that in the case of large castings weighing many tons, crystals of several cubic inches' capacity may be formed under special conditions of cooling. These, however, are quite rare, and possess the well-known dendritic or skeleton form. The majority of metals and alloys which have been hot-worked, have from 150 to 300 crystals to the linear inch, but frequently the size is still smaller, especially in steel. Rosenhain and Humphry* counted the number of crystals in a known area of mild steel, and from that calculated the areas of individual crystals. The figures they give are from 1·5 to $7{\cdot}5 \times 10^{-6}$ square inches, according to the condition of the steel. Sykes† has recently given as the diameters of crystals in molybdenum wire figures varying from 0·0011 to 0·0002 of an inch in diameter. These correspond to approximately from 1000 to 5000 crystals to the linear inch. Admittedly, in this case, the wire was severely worked.

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* 'Journ. of the Iron and Steel Inst.,' vol. 87, No. 1, p. 253 (1913).

† 'Bulletin of the American Inst. of Mining and Metallurgical Engineers,' February, 1921.

Sauveur* was one of the first investigators to show that by carefully straining and subsequently heating such metals, crystals of a much larger size could be produced, and suggested that there was a critical stress which produced the largest crystals.

Subsequently, Rüder,† Chappell,‡ Jeffries§ and Hanson|| have shown that if a metal is locally deformed, and then heated, exceptionally large crystals form at some distance from the point at which the stress is the severest. If a tapered test-piece is used, a strain gradient is obtained, and it is found that the largest crystals always form within the strained region, but further from the area of greatest strain the higher the temperature. In his experiments, Rüder strained strips of silicon-steel sheet to various extents, and found that the largest crystals were formed on heating after a certain deformation, but that as this was exceeded the crystals become gradually smaller. Seligman and Williams¶ stretched aluminium sheet, which had previously been heated, to various degrees, and found, on heating, that up to a certain point, a small deformation had no effect. Beyond this point, however, large crystals were formed, and, as the deformation was further increased, the crystal size was diminished. The crystals produced by these methods were very large compared with those in the original metal, some of them being 0·5 of an inch long.

In recent years wires have been produced, both of tungsten and molybdenum, in which the crystals occupy the entire cross-section of the wire. Indeed, considerable lengths of tungsten wire are now made for lamp filaments, which are composed of a single crystal.** This is done by drawing the tungsten through dies at a certain rate and temperature. The molybdenum wire tested by Sykes was prepared in the following way:—The wire of diameter 0·027 of an inch was equi-axed by heating in hydrogen for 5 seconds at 90 per cent. of its fusion amperage. The wire was then at a low red heat drawn through a 0·025-inch die and its cross-section reduced by

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* 'Proceedings of the International Assn. for Testing Materials, 6th Congress,' vol. 2, No. 6 (1912).

† 'Trans. of Amer. Inst. of Mining Engineers,' vol. 47, pp. 569–586 (1913).

‡ 'Journ. of the Iron and Steel Inst.,' 1914, No. 1, pp. 460–496.

§ 'Journ. of the Inst. of Metals,' vol. 20, No. 2, pp. 109–140 (1918).

|| 'Journ. of the Inst. of Metals,' vol. 20, No. 2, pp. 141–145 (1918).

¶ 'Journ. of the Inst. of Metals,' vol. 20, No. 2, pp. 162–165 (1918).

** 'Jahrbuch der Radioakt.,' November 15, 1918, pp. 270–292.

14 per cent. This wire was then heated in hydrogen. Sykes reports that many of the crystals extended completely across the diameter of the wire, and that the average diameter of the crystals was 0·013 of an inch, and the maximum length 0·5 of an inch.

In 1920 the present authors published the results of an extended investigation on "Crystal Growth and Re-crystallisation in Metals,"* in which were included a number of tests on the production of large crystals in aluminium sheet 0·125 of an inch in thickness, and their conclusions may be summarised as follows:—(1) The largest crystals are always formed at the minimum stress requisite to produce growth, which minimum is determined by the temperature of heating. (2) The lower the temperature of heating the greater the stress required to produce the largest crystals obtainable at that temperature. (3) There is no gradual increase in size from the original sized crystals up to the largest; the latter appear to form directly from them. (4) Test-pieces strained and heated at a low temperature, which nevertheless is sufficient completely to soften the metal—for instance at 350° C.—show no crystal growth at that temperature. Nevertheless, if subsequently heated at a higher temperature, they produce large crystals equal in size to those normally produced at that temperature for the same degree of elongation.

The purity of the aluminium upon which these experiments were carried out did not exceed 98·9 per cent., the principal impurities being silicon and iron. Later experiments showed that crystals of a much larger size could be produced in purer sheet. It was therefore decided to repeat the previous experiments with the purest obtainable metal. This was kindly furnished by the British Aluminium Company, and found to contain 99·6 per cent. of aluminium, the chief impurities being silicon 0·19 and iron 0·14 per cent. In the strain-hardened sheet the silicon appears to be wholly dissolved, but the greater part of the small amount of iron present was segregated as the aluminium-iron compound, $FeAl_3$. The total length of the test-pieces was 8·75 inches, with a parallel portion 4 inches long, 1 inch broad, and 0·125 of an inch thick. The broad ends were 2·75 × 1·75 × 0·125 of an inch. The test-pieces were in the first instance heated for 6 hours at 550° C., so as to remove all strain-hardness and produce uniform equiaxed crystals. This resulted in a material containing, on an average, 150 crystals to the linear inch. They were then stressed by varying amounts, shown in Table I, so as to produce extensions of 1 per cent., 2 per cent., 3 per cent., etc., on 3 inches until, at a stress of 4·7 tons per square inch, the total extension was 30 per cent. They were next heated for 18 hours at 550° C., and etched. The surface of the sheet was remarkably good, and required no preparatory treatment before etching. The results were similar to those obtained with the less pure sheet, except that the largest crystals were found in the test-piece which had stretched only 1 per cent. whereas in the latter case no growth was obtained under 3 per cent. extension at the same temperature. Moreover, more than half of the specimen, which had stretched only 1 per cent., consisted substantially of one crystal with a few unabsorbed small crystals on the surface. The crystals in those test-pieces which had received an elongation of 2 per cent. and upwards were all correspondingly smaller. Finally, the complete series of test-pieces—18 in all—were broken under tensile stress.

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* 'Journ. of the Inst. of Metals,' vol. 24, No. 2, pp. 83–131 (1920).

Table I.

Mark.	Percentage elongation given. Calculated on 3 inches.	Load tons per square inch required to produce elongation.	After heating for 18 hours at 550° C.	
			Ultimate stress tons per square inch. Calculated on new area.	Percentage elongation on 3 inches.
2	1	1·6	3·1	23
3	2	2·3	3·4	37
4	3	3·0	3·2	27
5	4	3·3	3·3	35
6	5	3·5	3·9	29
7	6	3·7	3·7	30
8	7	4·0	3·8	23
9	8	3·9	4·1	*22
10	9	4·1	4·3	*24
11	10	4·2	4·6	34
12	11	4·3	4·6	35
13	12	4·3	4·6	35
14	14	4·4	4·6	34
15	16	4·4	4·6	39
16	18	4·6	4·6	36
17	20	4·6	4·5	35
18	25	4·7	4·3	33
19	30	4·7	4·5	30

* Broke outside gauge marks.

The results of the tensile tests are given in Table I. It will be seen that the ultimate stress is lowest for the largest crystals, and that it increases fairly uniformly up to an initial elongation of 10 per cent., at which point it becomes steady until after an elongation of 20 per cent. when it falls slightly. The figures range from 3·1 to 4·6 tons per square inch. (The average breaking stress for the sheet as delivered, after it has been heated for 6 hours at 550° C., is 4·6 tons per square inch (Table II).) Slight variations in the figures can be ignored, since a uniform rate of loading is not possible in this material owing to large slips which take place in jerks. The extensions measured over 3 inches are very variable, particularly where the crystals are large. This is evidently due to the fact that in some pieces the crystals elongate more easily than in others, and this has a marked effect when the whole test-piece consists of comparatively few crystals. The low figure obtained for the test-piece, which had had a preliminary extension of 1 per cent., is partly due to the presence of small unabsorbed crystals on the surface.

Production of Single Crystals in the Sheet.

The problem which the authors next set themselves was to convert the crystals in the parallel portion of the test-piece, 4 inches × 1 inch × 0·125 of an inch, into a single crystal. As already stated, the number of crystals in a linear inch, after treatment for 6 hours at 550° C., was about 150. Calculation, therefore, shows that the total number contained in the parallel portion of the test-piece was about 1,687,000.

Before describing the experiments undertaken with this object, it is necessary to refer very briefly to certain results established by the authors in their paper previously referred to.* The structural changes produced in a crystal aggregate by deformation followed by heat may be summarised somewhat in the following way:—The first effects are slight. They are revealed by slip bands and in some cases, twins. The former are completely, and the latter to some extent, removed by heating. No change is observed in the shape of the crystals. The boundaries appear unaffected, and, apart from twinning, there is no change in orientation. Thus far, only the interior of the crystals is affected. No identities are lost. Somewhat greater deformation, however, produces crystal growth, and at this stage the boundaries of the crystals become active. The activity is shown in the capacity of the growing crystal to push forward its boundary in certain directions, thus invading other crystals. But, even at this stage, the orientation of the growing crystals is maintained. That of the crystals grown into is, of course, destroyed unless it happens to be the same. The third stage, produced by still greater deformation, appears to take place exclusively in the boundaries of the deformed crystals. It is here that the new crystals are born, indicating the destruction of the original crystals and a complete scheme of orientation. Whereas, therefore, the early effects of deformation are shown only in the interior of the crystals, the later ones appear to take place entirely at the boundaries.

The abnormally large crystals formed on heating, after a small deformation and the gradual decrease in their size as the deformation increases, are considered by the authors to be due to the following causes:—As already mentioned, the first effect of small amounts of deformation is to produce slip bands (and in some metals twins), but, provided the stress does not exceed a certain value, this is all that happens. A very little more deformation, however, causes a change in a few of the crystals, so that, on heating, they grow. The less the strain the fewer the centres from which growth will start, and hence the larger the crystals ultimately formed. In the case of the impure aluminium sheet, the largest crystals began to appear after 2 per cent. elongation, followed by heating at 550° C. But their capacity for growth was exhausted when only about half of the total number of crystals had been absorbed. At 645°, however, they were able to effect complete absorption, owing to the greater mobility conferred by the higher temperature. But the higher temperature enabled the growth to start from more centres, so that the final crystal size was smaller than at 550°. Similarly, as the deformation increases, more crystals will be strained to the critical amount to produce growth on heating, and there will accordingly be a corresponding decrease of crystal size. In a given case, where 2 per cent. elongation, followed by heat treatment at 500°, produced no growth, whereas 4 per cent. gave rise to the largest crystals, about ten crystals in all out of the many thousands present were strained in the critical amount, which enabled them to absorb all their neighbours on heating. It is, of course, possible to imagine a case in which only one of these crystals was strained to the critical amount which would have had to have been rather less. In this case it would be expected that the whole of the strained area would ultimately have consisted of one crystal instead of ten, provided that suitable conditions were maintained. One condition, which the authors regard as essential, is that all the remaining crystals must also be in a strained condition. As bearing on this, it should be pointed out that there was nearly always a strip of small unaltered crystals on either side of the flat ends of the test-pieces, even when they had been heated at 645° C., and that the large crystals showed no tendency to grow into them. Owing to their position, they had not been strained by the pulling of the test-piece. It seemed clear, therefore, that the crystals must all be strained to some extent if they are ultimately to be absorbed by one. The high temperature, if not absolutely necessary, is certainly a favouring condition, since it confers increased freedom of movement on the crystals, but the actual temperature at which growth progresses most favourably depends on the degree of deformation. The conditions laid down by the authors in their previous paper (p. 122) for the production of a single crystal were therefore "that every crystal in the complex shall be strained a certain small amount, and that one of them shall be strained rather more than all the rest." They went on to say "how unlikely it is that such a condition would ever be realised in practice it is unnecessary to emphasise, but, theoretically, such a case can quite well be conceived." This prognostication has not proved to be correct, and, before many months had passed, the authors had succeeded not only in converting all the crystals in the parallel portion of one test-piece into a single crystal, but had worked out conditions under which fully 25 per cent. of the test-pieces thus treated were converted into a single crystal. With regard to the remainder, some of them consisted of two, others of three, and others of four crystals, but it was very seldom that the last-named figure was exceeded.

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* 'Journ. of the Inst. of Metals,' vol. 24, No. 2, pp. 83–131 (1920).

To achieve these results, the high purity metal (99·6 per cent.), with which all subsequent experiments have been conducted, was subjected to three treatments, two of them thermal, the third mechanical. As received, the sheet was in the cold-rolled condition. It had first to be heated, so that it might be softened and re-crystallised. It had next to be strained to the required amount, and finally it required to be heated so that the potentiality of growth conferred by the stress could be brought fully into operation.

1. *The Temperature and Time of Heating before Stressing.*—The most suitable temperature was found to be 550° C. and the time 6 hours. If heating was continued for longer, large crystals formed on the surface of the sheet in many cases, and the test-pieces were rendered useless, because the stress subsequently applied produced a greater elongation, which was localised to a large extent in these crystals, and consequently the strain was not uniform. If heated at a lower temperature, the crystals finally produced on heating for a given load and elongation were smaller, but the results were very variable. The same result followed at 550° C. if heating was continued for a shorter period, for instance, 2 hours. In all such cases the results were very variable, but they tended to show that the largest crystals were more frequently formed when the temperature had been high and maintained for a sufficient period to produce stable conditions in the metal.

2. *The Stress applied and Percentage Elongation caused.*—In previous experiments the method adopted had been to stretch the test pieces in tension by a given amount measured by means of dividers on 3-inch gauge-marks. This method was not capable of very accurate adjustment and was discarded in favour of pulling with a given load and then measuring the extension. The advantage of this method was that the stress was always constant and the variations in elongation were very slight. Moreover, a large number of test pieces could be stretched with ease and rapidity. The procedure finally adopted was to pull to some definite fraction of a ton per square

inch, which would give approximately the required elongation. A load of 0·20 of a ton, *i.e.*, 1·6 tons per square inch, gave an elongation of 0·8 per cent. on 3 inches. If such a test-piece was subsequently heated, large crystals were produced, but small surface crystals frequently remained unabsorbed even after many hours' heating at 550° to 600°. A load of 0·30 of a ton finally proved the most suitable. This is equivalent to 2·4 tons per square inch and gave an average elongation of 1·6 per cent. on 3 inches.

3. *The Temperature of Heating after the Application of Stress.*—It was found that large crystals began to form usually at about 500° C., or even under in some specimens, but not until 520° C. in others, although the treatment had been identical in the two cases. It was also found that the lowest possible temperature at which growth took place at all was the most suitable for growing the largest crystals. Consequently, each test-piece was placed in a furnace whose initial temperature was 450° C. and the temperature raised at from 15° to 20° C. per day up to 550° C. It was then subsequently heated for 1 hour at 600° C. in order to complete the absorption of small crystals on the surface, which persistently remained at lower temperatures. This method proved, on the whole, to be the best; but even so, on an average not more than one test-piece in four is converted into a single crystal over the parallel portion of the test-piece. The time required for a single crystal to form from the 1,687,000 can only be stated approximately, for it has been found to vary within tolerably wide limits, and, as just mentioned, some of the small surface crystals only disappear after fairly prolonged heating, but in the majority of cases the result can be achieved in from 48 to 72 hours. A test piece is, of course, much more quickly converted into three or four large crystals than into one, since in the former case growth takes place simultaneously from several centres. In such cases, when the large crystals have set, the authors have not found that they grow at each other's expense, even if the temperature be raised or the time of heating extended. In this respect they resemble the crystals of castings which also grow from various centres until they meet and are then stable.

Certain variations of the above methods were subsequently tried, but none of them were found to give greater regularity of results, although some of them established facts which bear on the question of how single crystals are actually produced. Prolonged heating at a low temperature, or starting the heating from a low temperature, for instance 250°, and gradually raising it, was not found to affect the crystal size. It was established that if the test pieces were more severely stressed, the temperature at which the maximum crystal size was produced was lowered. It was, therefore, to be expected that, provided the temperature at which heating was commenced was sufficiently low, all the test pieces within certain limits of stress should give the same sized crystals on heating. A series of test-pieces was stretched 1, 2, 3, 4, and 5 per cent., heated at 250° C., and the temperature then gradually raised to 550°. In the pieces stretched from 1 to 4 per cent. the number of large crystals produced was approximately the same, although certain differences were manifest. In that stretched 5 per cent., however, the crystals were much smaller, indicating that, however much the temperature may be lowered, there is an upper limit to the stress which will produce the largest crystals.

If the optimum conditions for the production of a single crystal throughout the parallel portion of the test-piece are maintained, as previously described, on an average one experiment in four is successful. There are, however, considerable variations from batch to batch. For example, in a given case eighteen test-pieces, which had received, as nearly as possible, the same heat and mechanical treatment, gave the following results, which must be understood to refer only to the parallel portion of the test-piece, 4 inches × 1 inch × 0·125 of an inch:—Two test-pieces consisted of one crystal, six of two crystals, five of three crystals, three of four crystals, and two of six crystals. In another batch, out of twenty test-pieces, seven consisted of one crystal, eight of two crystals, four of three crystals, and one of four crystals. The best result hitherto achieved has been in a batch where nearly half the test pieces were converted into a single crystal over the length in question.

Tensile Strength Tests.

When composed of small crystals as obtained by heating for 6 hours at 550° C. the sheet gives uniform results on breaking. A few examples are given in Table VII, p. 342, from which it will be seen that the ultimate stress varies from 4·5 to 4·7 tons per square inch, and the percentage extension on 3 inches from 36 to 38. The sheet necks slightly at the fracture, which is usually straight. This is the standard of comparison from which the behaviour of single crystals may be judged. Its condition is described by the authors as "normal" and photograph is given in Plate 10, fig. 12. The roughening of the surface due to the large number of small crystals is evident.

The values obtained in tests of specimens consisting of single crystals varied from 2·80 to 4·08 tons per square inch, while the extension varied from 34 to 86 per cent. measured on 3 inches. These variations in properties were accompanied by differences in the method of stretching and type of fracture, and these differences have provided a means of classifying the test-pieces. In certain cases the mechanical properties, especially the extension, were found to be closely related to these characteristics. The test-pieces have been classified in the following five groups. Not all of them showed the various features to the same extent and some were almost on the border line between two groups:—

Type 1.—The test-pieces narrowed in breadth gradually from the shoulders towards the fracture. The reduction in breadth near the fracture was often great, *i.e.*, the metal necked sometimes almost to a point (Plate 9, fig. 2). The sides (machined edges of the sheet) remained perpendicular and the reduction in thickness was only from 2 to 3 per cent. Slip bands were usually absent from the surface, but large slips were frequent near the fracture, forming steps on the sides and smaller markings on the face.

It was noticed in some specimens that a large slip occurred over one half and this then held while a similar slip took place on the other half. The process was then repeated until the test-piece broke (fig. 3, and Diagram I). Slip in this case took place in the direction of pulling and at right angles to the plane of the sheet. With a view to following the distortion of the specimens during the test some of them were ruled in squares (0·25 inch) by means of a fine needle point. The results showed that the squares became diamond-shaped, that they had both narrowed and elongated and at the fracture the lines at right angles to the axis were frequently bent at an angle of 45°. Figs. 1 and 2, Plate 9, are examples of this type and fig. 16, Plate 10, shows the change in shape of the squares. The results of seven tensile tests will be found in Table II, from which it will be seen the extreme values for the tenacity were 2·9 and 3·9 tons per square inch and those of the elongation 57 and 67 per cent.

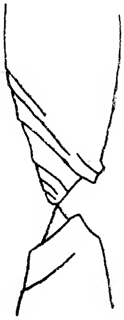


Diagram I.

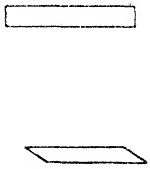


Diagram II.

Type 2.—In this case the test piece remained broad, losing sometimes only 1 per cent. in breadth, but became very thin with a uniform reduction of thickness of about 45 per cent. The sides tended to slope slightly in the same direction away from the perpendicular. Slip bands on the surface were well marked and their main direction was across the test-piece, that is, at right angles to the axis. There was no necking at the fracture, the test-piece remained broad but drew down to a knife edge and then parted in a straight line, either at right angles to the axis or inclined at some other angle to it. If the test-pieces were marked in 0·25 or 0·50 inch squares before being pulled the lines at right angles to the axis did not become inclined to the same extent as in specimens of Type 1. They merely drew further apart, while the position of the lines parallel to the axis did not alter. Although the squares were only lightly scratched on the surface with a needle point, the cross lines affected the internal structure to such an extent that they were revealed on the opposite side of the test-piece by means of interruptions in the slip bands (fig. 3, Plate 9). This phenomenon was only met with in specimens of this type and is no doubt due to the particular direction of the slip bands in relation to the stress. This type, therefore, shows slipping in the plane of the test-piece in the direction of the stress (figs. 3 and 4, Plate 9). Fig. 13, Plate 10, shows test-pieces which had been marked in 0·25-inch squares before being pulled. Values obtained in the tests will be found in Table III. from which it will be seen that the ultimate stress varied from 2·8 to 3·3 tons per square inch and the extension from 47 to 73 per cent.

Type 3.—In these cases the test-piece both narrowed and thinned uniformly. There was no necking at the fracture, which went straight across the test-piece, as in Type 2, either at right angles to the axis or inclined at some other angle. A notable feature of this type is the sloping of the sides, so that a section after pulling is no longer a right angle but a parallelogram with alternate acute and obtuse angles. The side-ways slipping, which caused the test-piece to take this form, was entirely absent from Type 1, and only occasionally slightly evident in Type 2. It always occurs in this group, although not always to the same extent. Slip bands were usually well worked, and were inclined to the axis at different angles. Squares marked on the specimens by a needle-point both narrowed and elongated, and became diamond-shaped owing to the lines at right angles to the axis inclining towards it. Although similar in that respect to Type 1, they differed in that the diamonds were more uniform in size and shape over the whole test-piece. In other words, the elongation was more general and uniform. This type, in contra-distinction to the two previous ones, shows slipping in two main directions. It elongates in the direction of the stress by slips nearly parallel with the plane of the sheet, and also at right angles to the plane of the sheet but parallel with the axis. Inasmuch as these planes are not at right angles to the direction of the stress, there is also a sideways slip as the crystal endeavours to accommodate itself to it, and this accounts for the change in shape of the cross-section of the test-piece. Table IV gives the results of fifteen different tests in which the extreme values for the ultimate stress are 2·9 and 4·08 tons per square inch while the extension over 3 inches varies from 34 to no less than 86 per cent. There are greater variations in tensile properties in this group than in any other. Examples will be found in figs. 5, 6 and 7, Plate 9.

Type 4.—This unites the qualities both of Type 1 and Type 3, in that the test-pieces not only narrowed and thinned, but in addition, necked at the fracture. In all cases a sideways slip was evident. The actual values obtained in the tests will be found in Table V. With one exception, the ultimate stress values are very similar, while the extensions were in all cases high, partly owing, no doubt, to the necking at the fracture. An example of this type is seen in fig. 8, Plate 9, while figs. 14 and 15, Plate 10, show the distortion of the 0·25-inch squares as a result of the stress.

Type 5.—In this are included all the test-pieces which produced twins on being pulled. No signs of these were visible before stress was applied. In some cases only a few resulted; in others the test-piece was twinned all over. In every case the test-piece buckled and crumpled to a certain extent owing to the shifting of portions of the sheet into the twinning position. The slip bands change in direction as they cross the twin boundary, and where the specimen had been marked in squares these also change direction sharply at the twin boundaries. On heating, re-crystallisation began at these boundaries (fig. 17, Plate 11), although a section cut through this failed, under vertical illumination, to show the well-defined line associated with crystal boundaries. Under oblique illumination, however, the change of orientation is quite evident. Two types of twins were met with. The first resembled the twins produced in tin and zinc, although, owing to the large size of the crystals, they were on a much larger scale. They appeared like large fibres. A fracture across them was uneven, and the thickness of the sheet at the fracture differed from twin to twin. Examples are given in figs. 9 and 10, Plate 10. The second type of twinning observed was one in which the twinning planes were almost straight. Such a twin is shown at the top of the test-piece indicated in fig. 11, Plate 10. It appears as a narrow, dark line starting just at the shoulder of the test-piece, and running up into the broad end. Twins of this type also formed frequently on each edge of the test-piece. In a given case, on one side the entire edge turned up, while the edge on the opposite side turned down. Figs. 18 and 19 show a part of the surface in which, in addition to twinning on the edge, a twin has also been formed at the centre. A section of this crystal (fig. 19) shows how the twins at the edges turn in opposite directions, and also the step up at the twin in the centre. It will also be noticed that the twinning planes across the crystal are all parallel. As in the previous case, under vertical illumination, no line marks the boundary between the twins, but they are rendered perfectly clear by oblique illumination. This type of twinning is similar to that produced by the well-known method of causing twinning in calcite. By pressing a knife on the acute angle of a calcite rhomb near the edge, a portion of the crystal can be bent right over, making a definite angle with the unaltered face. This experiment was first performed by Baumhauer. The test-pieces which showed twinning were usually broad and thin, resembling Type 2. Twins were sometimes found amongst specimens of the other types, particularly near the boundary of an intruding crystal as, *e.g.*, in the lower half of fig. 11, Plate 10. Numerical values of the tests of this type will be found in Table VI. The figures of the percentage extension are the most uniform of the five types.

Table II.

Type.	Test-piece number.	Tensile strength. Tons per sq. in.	Elongation per cent. on 3 inches.
I. Test-pieces necked, thick, straight sides. Slip bands usually absent on surface.	22	3·1	66
	83	3·3	59
	98	3·5	57
	125	3·9	58
	130	2·9	65
	134	3·7	63
	210	3·1	67

Table III.

Type.	Test-piece number.	Tensile strength. Tons per sq. in.	Elongation per cent. on 3 inches.
II. Test-pieces broad and thin, straight fracture, slightly sloping sides. Slip bands nearly at right angles to axis of test-piece.	102	2·9	52
	172	3·1	65
	186	3·1	47
	198	3·3	67
	204	2·9	66
	264	3·1	74
	285	2·8	73

Table IV.

Type.	Test-piece number.	Tensile strength. Tons per sq. in.	Elongation per cent. on 3 inches.
III. Test-pieces narrow and thin, straight fracture, sloping sides. Slip bands sloping in relation to axis.	68	3·2	64
	74	3·3	48
	84	3·1	75
	114	3·1	58
	118	3·0	74
	119	3·3	55
	135	3·4	53
	191	3·1	60
	197	3·1	59
	207	3·1	74
	218	3·1	44
	252	3·8	34
	256	2·9	86
	261	3·1	76
	269	4·08	64

Table V.

Type.	Test-piece number.	Tensile strength. Tons per sq. in.	Elongation per cent. on 3 inches.
IV. Test-pieces narrow and thin, straight fracture necked, sloping sides. Slip bands sloping in relation to axis of test-piece.	96	3·2	66
	132	3·8	62
	184	3·1	75
	189	3·1	60
	194	3·1	76
	214	3·1	79
	220	3·3	53
	263	3·2	75

Table VI.

Type.	Test-piece number.	Tensile strength. Tons per sq. in.	Elongation per cent. on 3 inches.
V. Crystals twinned; other features variable.	82	3·4	55
	86	3·0	67
	116	3·0	56
	213	3·8	57
	270	3·0	55

Table VII.

Condition.	Test-piece number.	Tensile strength. Tons per sq. in.	Elongation per cent. on 3 inches.
Sheet as received, heated 6 hours at 550° C. About 150 crystals to the linear inch.	111	4·5	38
	289	4·7	37
	290	4·7	37
	291	4·6	37
	292	4·5	36

Stress Tests of Test-Pieces consisting of two Crystals.

Each crystal in a test-piece consisting of two or more crystals behaves according to one of the five types described above, provided that the whole test-piece at the point of fracture consists of a single crystal. A considerable number of specimens composed of two crystals were fractured in tension and almost every combination of the five types was met with. In the majority of cases tested the crystals occurred end to end in the test-piece and fracture always took place across one or other of the crystals, but never at a boundary. The influence of one crystal in giving support to the other at the boundary was most marked. Its effect was often noticeable at a distance of 0·25 inch from the boundary. Reduction, both in thickness and breadth was much less at this point and the power to withstand deformation was considerably increased, especially where one crystal slipped to the left and the other to the right. The metal drew down on either side of the boundary and left it as a ridge sometimes pronounced in thickness, at other times in breadth. In many cases the sheet looked as if it had been twisted in testing. It is not difficult, however, to account for these irregularities when it is remembered in what different ways the single crystals extended in tension. A crystal which narrowed on pulling in contact with one which remained broad tended to make the latter narrow also, with the result that it frequently wrinkled and twinned, in the vicinity of the boundary. In its turn, the crystal which remained broad, tended to prevent the other one from narrowing and this produced a thickening of the latter. Figures of some of these test-pieces show the effects referred to above. In fig. 20, Plate 11, will be observed three test-pieces in which the distortion at the junction of the two crystals is very manifest. Fig. 21, Plate 12, gives an edge-wise view of five fractured test-pieces in which in each case the combination of types there included is mentioned. This shows very clearly the different extents to which the crystals have been distorted and the influence of the junction.

In cases where two crystals existed side by side in the test-piece fracture occurred across them and one crystal frequently broke before the other. In this case the latter crystal continued to elongate until it also broke, with the result that when the test-piece was subsequently put together there was sometimes a gap of 0·25 inch between the fractured halves of the first crystal. A list of tests carried out on 18 test-pieces consisting of two crystals is given in Table VIII. As in the case of single crystals the values both for tenacity and extension are very variable. The elongation values are, for the most part, somewhat lower but the total elongation gives no indication of the amount of stretch on each individual crystal. When the test-piece was marked in 0·25 or 0·5 inch squares before pulling, it was possible to measure the elongation on 1 inch in each crystal and the figures so obtained have been included in a few cases. These are not strictly comparable as one of them includes the fracture. In the following examples, however, fracture occurred outside the gauge marks and the figures represent the actual elongation of each crystal under the same load:—

Total elongation on 3 in.	Crystal No. 1 on 1 in.	Crystal No. 2 on 1 in.
49 per cent.	71 per cent.	25 per cent.

The crystals in each case are classified according to the five types previously described. The great majority of combinations are represented in this list.

Table VIII.—Test-pieces consisting of Two Crystals.

Mark.	Tensile strength. Tons per sq. in.	Percentage elongation on 3 inches.	Type of crystals.		Percentage elongation on each crystal on 1 inch.	
			Fractured.	Other.	Fractured.	Other.
42	3·2	32	Type I	Type III		
75	3·2	54	,, IV	,, III		
81	3·5	29	,, III	,, III		
87	3·1	55	,, IV	,, III	61	52
122	3·0	46	,, V	,, I		
123	3·0	38	,, II	,, II	67	29
126	3·2	51	,, III	not altered		
129	2·9	68	,, II	Type III		
138	3·0	49	,, II	,, III		
145	2·9	66	,, III	,, III		
156	2·8	48	,, V	,, III		
251	2·9	42	,, III	,, III		
253	3·1	70	,, IV	,, IV		
265	3·1	63	,, V	,, II	71	63
271	3·2	50	,, I	,, II	86	29
279	3·1	51	,, II	,, II	81	17
280	3·5	55	,, II	,, III	94	17
281	3·0	48	,, III	,, V		

Test-pieces consisting of Three Crystals.

The results very much resemble those obtained with the test-pieces consisting of two crystals. The type of crystal which fractured could be judged without difficulty, but it was sometimes quite impossible to identify the others, especially if they did not undergo much deformation when fracture occurred. A few examples are given in Table IX. In all of these, each crystal extended over the entire cross-section of the test-piece. They were joined end to end. Here also fracture always occurred across a single crystal.

Table IX.—Test-pieces consisting of Three Crystals.

Mark.	Tensile strength. Tons per sq. in.	Percentage elongation on 3 ins.	Type of crystal.		
			Fracture 1.	Fracture 2.	Fracture 3.
127	3·5	36	Type III	Type III	Type III
144	2·9	55	„ V	„ V	„ II
154	3·1	39	„ V	„ II	„ II
272	3·1	53	„ IV	„ II	„ I
278	3·0	54	„ I	Not much altered: doubtful	Not much altered: doubtful.
284	3·1	44	„ II	Type I	Not much altered: doubtful.
287	3·6	37	„ III	„ III	Type I (probably).

The malleability of the single crystals was very remarkable. In a given case, a crystal was rolled down from the original thickness, 0·125 of an inch. At a certain stage, when it had elongated considerably, it was cut in half, and one of these pieces was rolled down to 0·0094 of an inch, corresponding to a reduction in thickness of 93 per cent. This rolling was done without any annealing, the strip was still quite malleable, and the operation could have been continued further had the rolls permitted it. This malleability is far in excess of that of the sheet, consisting of 150 crystals to the linear inch.

Production of Single Crystals in Bars.

Experiments were next carried out with a view to converting the crystals in a bar of the metal into a single crystal. One inch diameter bars of the same purity as the sheet were obtained by the kindness of the British Aluminium Company. Two sets of test-pieces were machined from them, the diameters being 0·564 and 0·798 of an inch respectively, with a parallel portion of 3·5 and 3·0 inches respectively. These were heated at 550° C. for 6 hours, and given an extension of 2 per cent. on 3 inches and heat treatment, as in the previous tests. On one occasion, out of eighteen test-pieces, eight consisted entirely of a single crystal, and, in three others, one or more small crystals intruded at the shoulders only. The mechanical properties were found to vary in much the same way as in the sheet, and the actual results will be found in Table X. No. 7·7, which has an elongation of 87 per cent. without fracture, being complete, is comparable with the highest elongation obtained with sheet, viz., 86 per cent. The specimens marked with a star were removed from the machine at different stages before fracture was complete, so as to study method of fracture. The elongations are therefore lower than they would have been if the two halves had actually parted.

Table X.—Mechanical Properties of Bar 0·564 of an inch in diameter.

Mark.	Tensile strength. Tons per sq. in.	Percentage elongation on 3 ins.	Number of crystals in bar.
3·10	3·4	76	One crystal.
3·29	3·0	76	,, small one at shoulder.
3·30	3·0	78	,, which twinned on pulling.
3·31	3·1	68	,, small crystals at each shoulder.
3·37	4·0	71	,,
10·30*	3·3	56	,,
10·31*	3·5	60	,, small one at shoulder.
10·33	3·9	55	,, two small ones one end.
7·5*	3·8	65	,, small one at shoulder.
7·7*	3·06	87	,,
3·32	3·4	59	Two parallel crystals, fracture across two.
3·33	3·7	40	Two small parallel crystals at one end: the rest consisted of one crystal in which fracture occurred.
3·35	3·4	66	Three crystals, fracture in one.
3·36	3·1	64	Two parallel crystals at one end; the remainder consisted of one crystal in which fracture occurred.
3·39	3·3	69	Two crystals, fracture across one.
3·41	3·1	77	,, ,, ,,
3·42	3·5	50	One crystal at each end and one in the middle across which fracture occurred.
7·8	3·3	50	Two crystals, fracture across one.
10·1	4·82	44	Bar consisting of small crystals.
10·2	4·88	44	Heated for 6 hours at 550° C.

Except that some of the crystals twinned on pulling, there were no different types of fracture such as were found in the sheet. Where a crystal occupied the entire cross-section, the test-piece, flattened in one dimension sometimes as much as 45 per cent., whereas the other dimension differed but little from the original diameter of the bar. Diagram III shows (1) a section of the original bar; (2) a section after pulling; and (3) a section at the fracture.

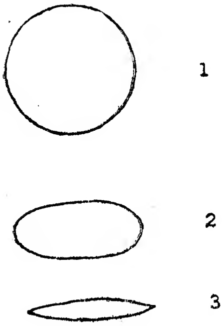
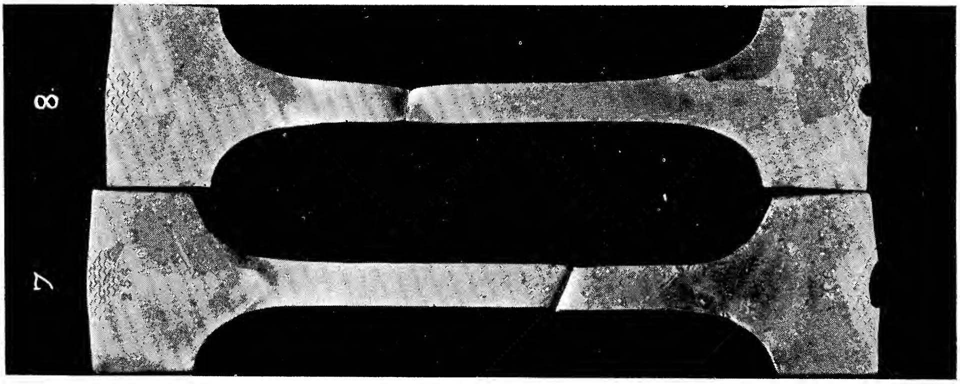


Diagram III.

The method of fracture was peculiar, and can best be described with the aid of diagrams. When the bar began to break, it drew down sharply in the same direction in which it had thinned, and a lens-shaped area was formed (Diagram IV, fig. 1). As the bar pulled apart, this became smaller and smaller (fig. 2). It parted first on both sides, and then in the middle (fig. 3). A section cut through the fracture illustrates the thinning at right angles to the plane, depicted in figs. 1, 2, and 3, and shows the curious grooved fracture with flow lines (dotted, fig. 4), which was always obtained. This type of fracture was found in all the bars where fracture actually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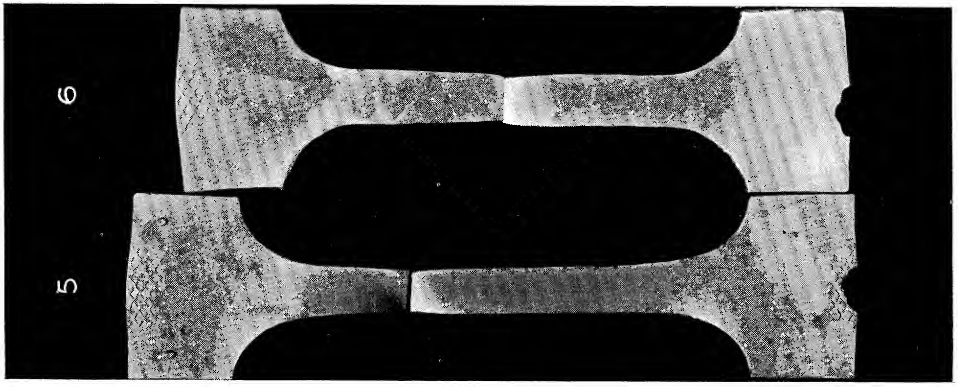
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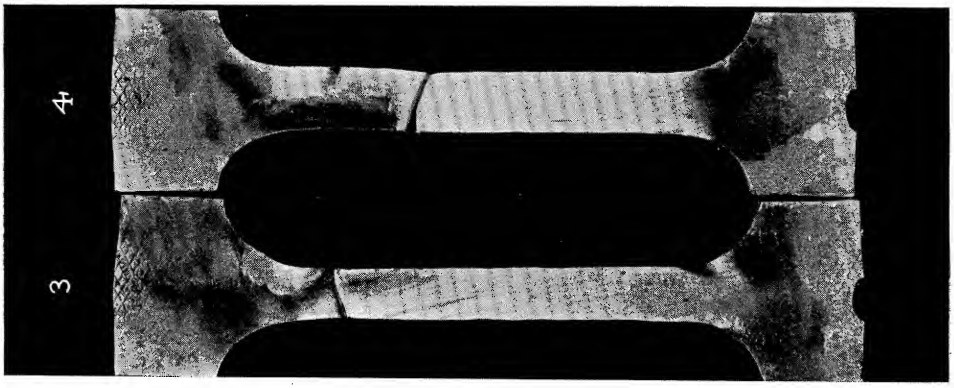
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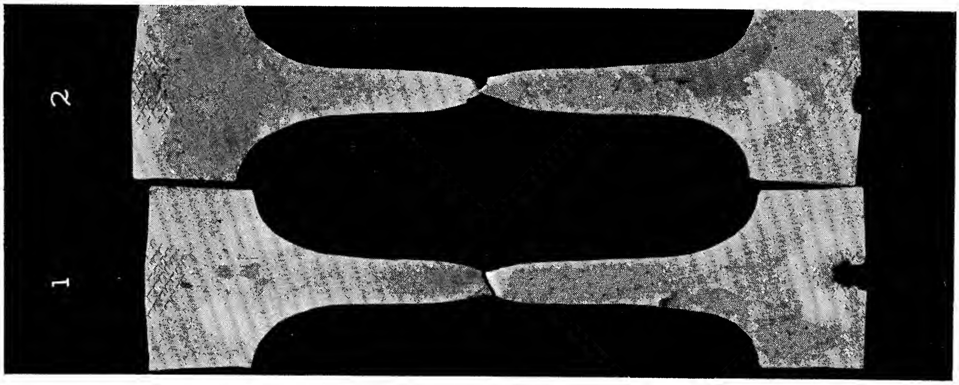
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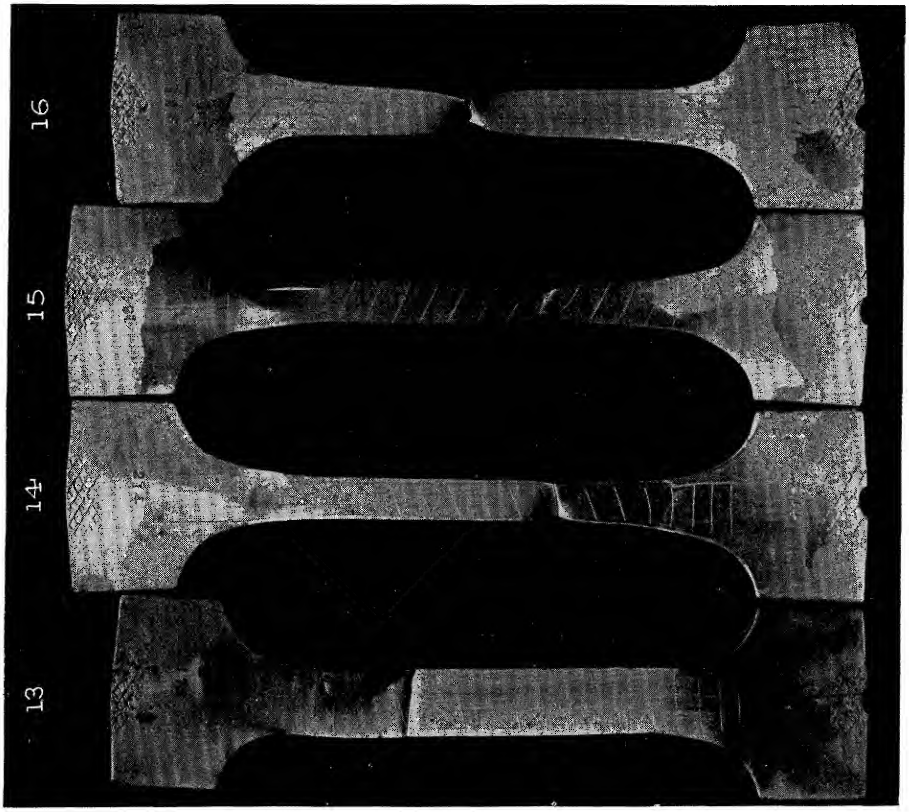
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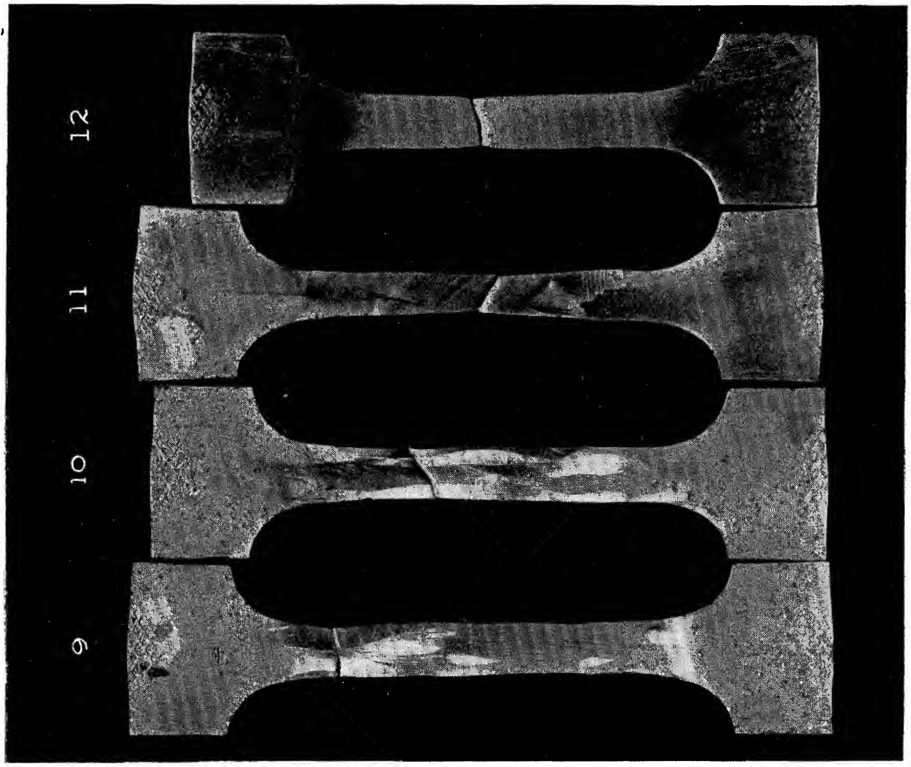
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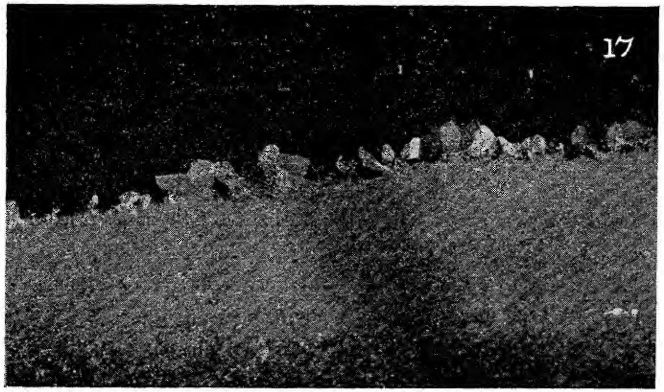

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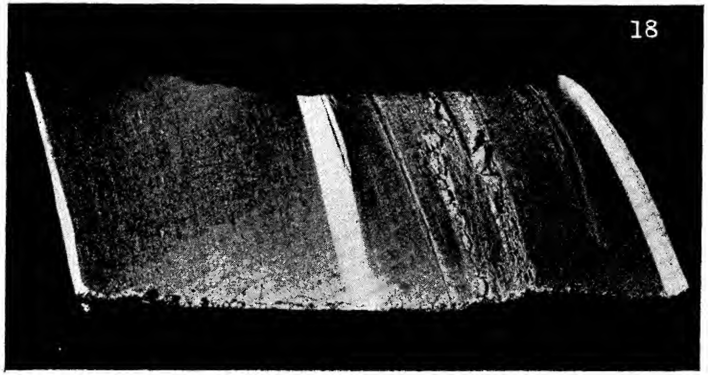

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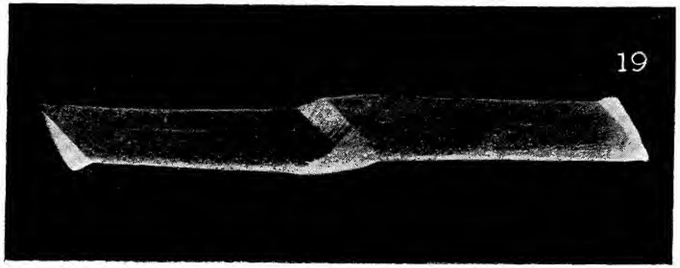

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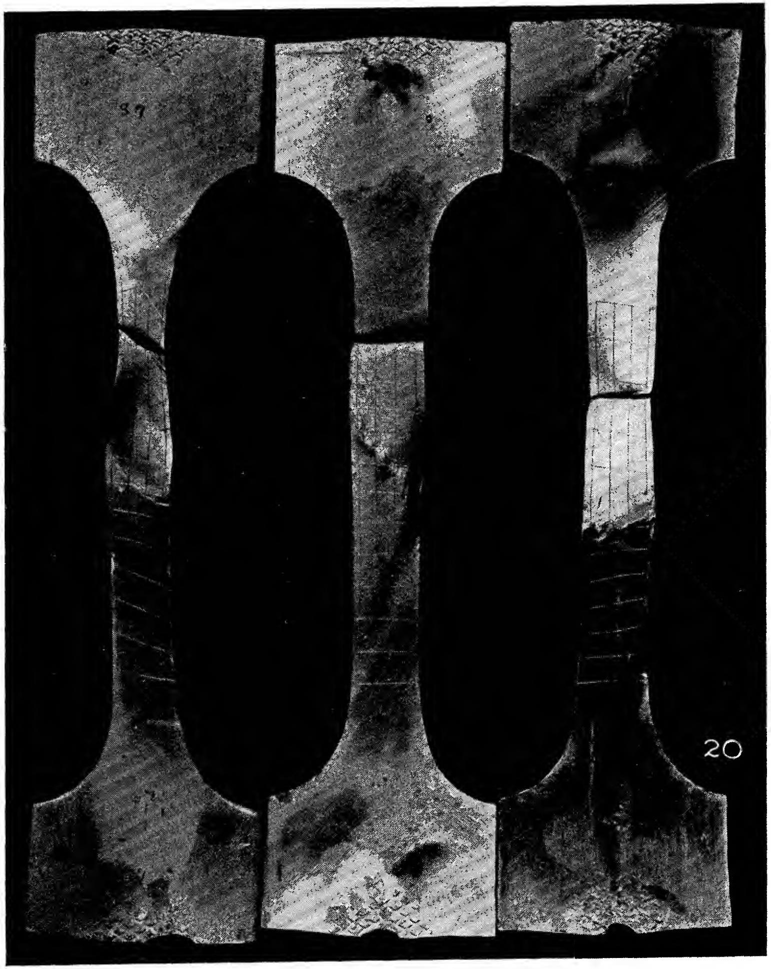

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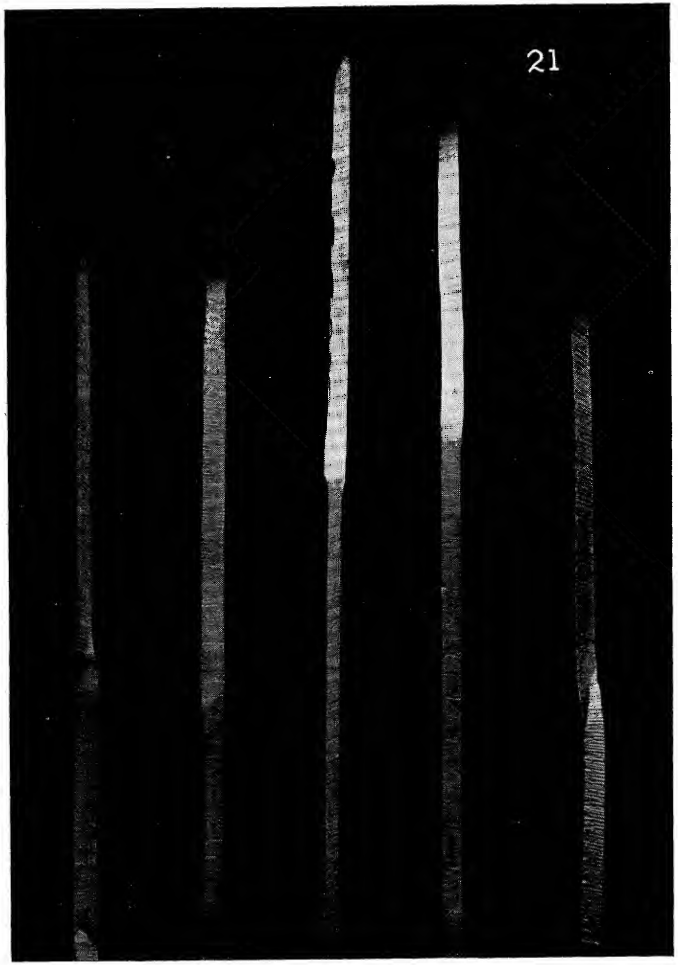

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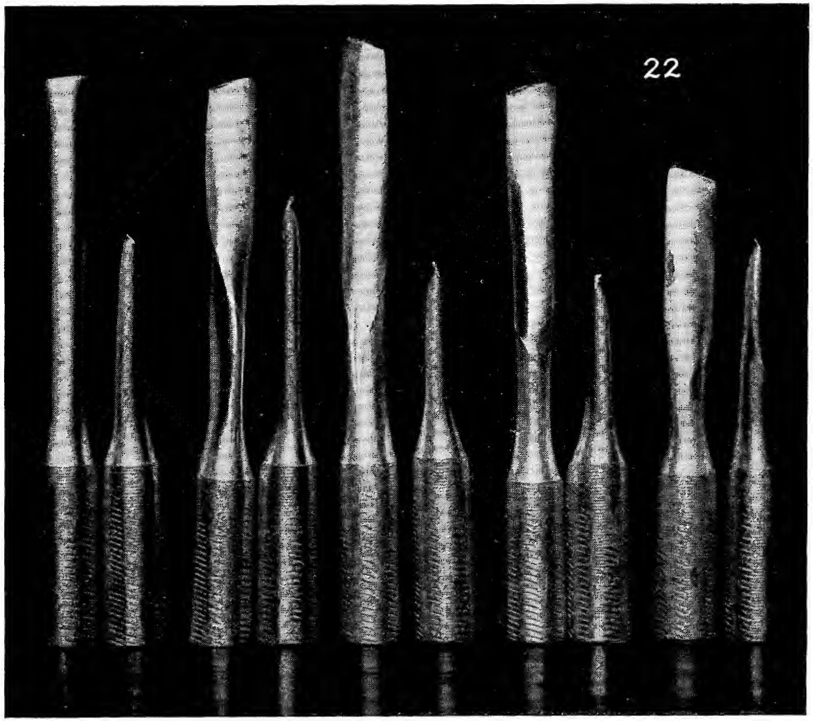

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occurred across single crystals. It is quite unlike that of a similar test-piece composed of small crystals, where the section of the bar remains round and necks uniformly. Photographs of some of these bars are given on Plate 12, fig. 22. In each case one half of the test-piece is placed so as to show the broad side, while the other half is turned at right angles to show how the test-piece has thinned. Nos. 30 and 37 were single crystals, the latter twinned on pulling: the remaining three consisted of two crystals. It will be observed in Table X that the tensile strength of the single crystals varied from 3·0 to 4·0 tons per square inch, whereas that of the bar, composed of 150 crystals to the linear inch, was 4·85 tons. The malleability of the single crystals is markedly higher than that of the bar consisting of small crystals.

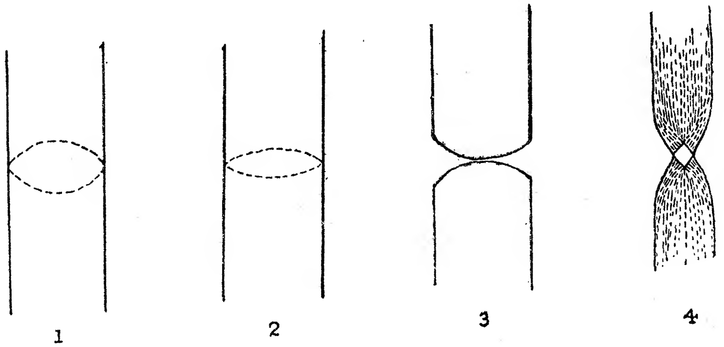

Diagram IV.

Considerably more difficulty was experienced in converting the crystals in the 0·798 of an inch diameter bar into a single crystal. After several attempts, however, bars were obtained in which single crystals extended over the entire cross section. In one case the whole of the parallel portion of the test-piece was found to consist of one crystal, while in several others more than three-quarters was thus occupied. Many of the bars consisted of two crystals, but in the majority of cases these existed side by side and not end to end, so that fracture always occurred across both of them. The majority of these bars twinned on pulling, so that the fracture was often uneven and did not show the definite shape obtained in the 0·564-diameter bars. The tensile properties of several bars of this diameter will be found in Table XI.

Some of the original bars, 1 inch in diameter, and some of which only sufficient was removed to reduce the diameter to 0·9 of an inch, were reduced in the same way, but in no case was a crystal obtained extending over the whole diameter of the bar. A cross section usually showed three crystals, but occasionally there were two. Some of the crystals, however, grew to a length of 7 or 8 inches. In addition to round bars, 1-inch square bars were

Table XI.—Mechanical Properties of Bar 0·798 of an inch in diameter.

Mark.	Tensile strength. Tons per sq. in.	Percentage elongation on 3 ins.	Number of crystals in bar.
2·3	4·1	53	Two crystals almost parallel.
2·9	3·9	66	One crystal down one side, two on the other.
2·11	3·8	71	One crystal all down one side, three on the other.
10·17	4·0	42	One crystal extending over the whole section across which fracture occurred. Two crystals at the other end.
10·20	3·8	51	Two crystals, both extending over the whole section. Fracture occurred across one.
10·24	4·1	47	One crystal and two small ones—one at side, one at end.
10·25	4·0	53	One single crystal and a small crystal in one shoulder.

treated. Owing to the shape, these failed to strain uniformly, and on heating, crystals grew from the four corners and met in a line in the middle of the four sides. Some of the crystals were from 2 to 3 inches long and were visible on two adjacent sides. Remarkable effects were obtained on breaking such bars. In some places the corners became rounded, while in others they were narrowed to a ridge almost of a knife-edge thinness. The whole bar became very much twisted and distorted. An attempt was made to measure the Brinell hardness number on two adjacent sides of the same crystal. The lowest available load was 500 kgrm. and the depression made was so large, owing to the softness of the metal, that it could not be made on one side without affecting the other. It was, however, possible to make depressions in some crystals which were sufficiently near the centre of the bar to obviate all risk of being affected by the edges. These were not round, as is the case with metal consisting of small crystals. Most of them were almost square with rounded corners, but they differed from crystal to crystal according to the orientation. Depressions made at a crystal boundary were very distorted. Diagram No. 5 shows Brinell depressions produced in three crystals.

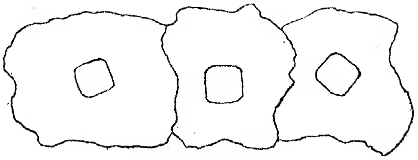

DIAGRAM V.

The effect of heat on the broken test-pieces was to bring about recrystallisation, *i.e.*, the birth of new differently oriented crystals. The temperature at which this began and the size of the new crystals produced depended on the amount of deformation of each particular crystal. The crystals which had been least deformed produced the largest new crystals. It was always found that the new crystals grew from the region of maximum stress, *e.g.*, from the fracture itself, from scratches on the surface, and from crystal or twin boundaries. On heating a broken single crystal the smallest of the new crystals are found at the fracture, and the size increases up to the shoulders, where the stress has been least. The new crystals were elongated in the direction of pulling, but frequently sloped sideways, as if following the direction of the slip bands. Some of the new crystals showed well-marked twins, resembling those in copper and brass, and one example was obtained in which the twinned crystal completely penetrated the sheet.

In the preceding pages, a description has been given of the methods whereby single crystals of aluminium have been produced, and their behaviour under tensile stress examined until fracture occurred. It is very remarkable that such extremely large crystals can be produced with comparative ease. As already mentioned, the number of crystals in the original sheet or bar, after the first "normalising" heat treatment, was about 150 to the linear inch. In the case of the sheet, in which the parallel portion is $4 \times 1 \times 0{\cdot}125$ of an inch, the number of crystals absorbed by the growing crystal must have been in the neighbourhood of 1,687,000. Indeed, since most of the single crystals grew well up into the shoulders of the test-pieces, the number must have been considerably more. In the case of the bars, 0·564 inch in diameter, where single crystals were obtained which occupied the whole of the region between the shoulders, *i.e.*, 4·5 inches (the parallel portion is 3·5 inches), the total volume of the crystal was rather more than 1 cubic inch since it grew well up into the shoulders at both ends. This must have been produced, therefore, from about 3,500,000 crystals. Finally, in the case of the bar, 0·798 inch in diameter, in which a crystal was obtained occupying the whole of the region between the shoulders, its volume was more than 2 cubic inches and the number of crystals which were absorbed in its formation must have been about 7,000,000.

An explanation of the experimental facts set forth in the present paper requires a completer knowledge of the aluminium crystal and the effect upon it of tensile stress than yet exists, but it is well that possible explanations should be considered even in the existing state of imperfect knowledge if only because the attempt will show in what directions further research is needed.

Crystals are usually classified according to their external geometrical form, to which their properties are found to be closely related. This method cannot be applied to determine the system to which metallic crystals, produced as above, belong, since they do not possess the external forms of crystals but take their shape from the test-piece in which they have grown. They are allotriomorphic. Each crystal in the original sheet or bar, which contains 150 to the linear inch, has grown from a centre and its boundary is formed by contact with those of other growing crystals. As the rate of growth is not the same in all directions these boundaries are quite irregular in shape, but in an unstressed metal they are, broadly speaking, equi-axed, irregularly-shaped polyhedra. In spite of the absence of external geometrical form metallographic research has established the fact that these polyhedra are true crystals. In the original bar or sheet from which the stress due to working has been removed by preliminary heat treatment at 550° C., these minute crystals are oriented at haphazard.

Hull* has recently investigated the structure of aluminium crystals in a finely crystalline aggregate and concluded that the pattern thus obtained corresponds to a face-centred cubic lattice. Prof. Sir William Bragg has kindly examined several of the single crystals obtained in the sheets of the authors, and has come to the same conclusion. His experiments have removed all doubt as to the sheet being a genuine crystal, and have confirmed the view held by metallographists that etching is a reliable method of distinguishing crystals in a metal. Aluminium crystals, therefore, belong to the cubic system, and must have properties consistent with those of that group. The cubic system possesses the highest degree of symmetry, both external and internal. Investigations of the properties of crystals in this system indicate that the crystals are isotropic to the passage of light, heat and electricity, and expand uniformly in all directions. As regards elasticity, hardness and conduction of sound, it has been found that the values vary in different directions. These properties, however, are closely related to the symmetry, since maximum and minimum values have been found to coincide with axes of symmetry.

Differences of cohesion and hardness in different directions explain the variations in the tensile properties of the test-pieces which have been found. Although the single crystals obtained in the sheet have been formed in the same-shaped test-piece, their orientation relative to the stress obviously varied considerably, and may not have been precisely the same in any two of the cases tested. It will depend upon that of the crystal which grew. Both in the case of the sheet and the bar, the shape alters when stress is applied, since slip and deformation take place only on certain planes, and the changes in shape observed correspond to the attempt of the crystal to accommodate itself to the stress. Jeffries and Archer† have recently predicted what the shape of a square test-piece should be after being pulled, supposing that this consisted of a single crystal, and that the planes of slip were at an angle of 45° to the stress. They concluded that the test-piece should be reduced in thickness in one dimension only, and that the fracture should be wedge-shaped. The bars tested by the present authors all show a wedge-shaped fracture, although there is every reason for supposing that the original orientations were not all identical, and this means that, under the stress, some of the bars must have altered their shape considerably in accommodating themselves to it. The extreme variations in ultimate stress found in single crystals produced in the sheet are 2·8 and 4·08 tons per square inch. It is somewhat surprising that the tenacity of the sheet, composed of 150 crystals to the linear inch, is not higher than 4·66 tons per square inch, for it has usually been supposed that metals owe much of their tenacity to the fact that they are aggregates of small crystals oriented at haphazard, and consequently that slip can only occur to a very limited extent in the planes of those particular crystals which happen to be oriented in the direction of minimum cohesion relative to the stress, and that the adjacent crystals thus support them.

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* 'Amer. Inst. Elec. Engineers,' vol. 38, Part II, October, 1919.

† 'Met. and Chem. Engineering,' vol. 21, No. 24, June 15, 1921.

The formation of the single crystals described in the foregoing paper does not differ in character, but only in degree, from the production of large crystals described by the authors in the previous paper.* They were led at that time to put forward the suggestion that the crystals which grew were slightly more strained than their neighbours, because they had come to the conclusion that mechanical deformation supplied the energy for crystal growth, and that heat only permitted changes to take place which deformation rendered possible. Consequently, the more the crystals were strained the greater the energy they possessed. Mr. U. R. Evans, in a communication on the paper referred to,† suggested that it was to be expected that the less deformed crystals were the most active in crystal growth, and that the more strained crystals aligned themselves upon them. He also stated that growth appeared to depend more on the difference in the degree of deformation existing between certain crystals than on its absolute amount, although there appeared to be a minimum value below which no growth occurred. Mr. Evans' suggestion, however, is in conflict with the fact that as the deformation is increased the crystal size diminishes—in other words, growth starts from more, instead of fewer, centres. His suggestion requires the latter.

The question, however, cannot be satisfactorily settled until more is known of the changes which take place in a crystal when it is plastically deformed. Knowledge of this subject at the present time rests principally upon the classical researches of Sir George Beilby. It appears, however, to the authors that the energy of growth cannot be stored in the amorphous vitreous films which, according to him, are the cause of work-hardness in metals, since the growth of single crystals in the aluminium sheet takes place at a considerably higher temperature than that at which the complete softening of the work-hardened metal is effected. Accordingly, all the vitreous amorphous metal must previously have recrystallised. It is, moreover, difficult to explain why the least deformation should produce the largest crystals on heating if growth depends on the presence of amorphous metal. Sir William Bragg has kindly agreed to collaborate with the authors in a joint investigation of this question, and they are hopeful that, as a result of the X-ray analysis of large crystals, such as their experiments have rendered available, which can be strained to any required extent, it will be possible to ascertain what happens to the arrangement of the atoms in the space lattice under these conditions. If this is the case, it is almost certain to throw light on the cases of crystal growth recorded in the present paper. In the meantime and with a view of meeting Mr. Evans' criticism, it may be suggested that, instead of a more highly energised crystal growing direct, it deposits first of all a new crystal nucleus; in other words, a very limited form of recrystallisation takes place. This new crystal is by hypothesis quite free from distortion and can absorb all the strained crystals in the test-piece. Against this view may be urged certain objections based upon experimental facts observed in the research.

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* 'Journ. of the Inst. of Metals,' vol. 24, No. 2, pp. 83–131 (1920).

† 'Journ. of the Inst. of Metals,' vol. 25, No. 1, p. 299 (1921).

1. If a test-piece consisting of a single crystal is stressed so as to produce an extension of 2 per cent. on 3 inches, this is insufficient to enable it to re-crystallise on heating at 550° C. or even at 600°. It is probable, therefore, that this treatment is not sufficient to enable crystals in a crystal aggregate to re-crystallise.

2. When a sheet or bar is heated at 550° after being rolled it re-crystallises in about 1 hour and after that little change is evident for some time. If the heating is continued for 24 hours or several days, according to the purity of the metal, large crystals form which originate at the surface and sometimes grow right through the sheet. There is no evidence of spontaneous re-crystallisation having taken place, and it is possible that the surface was in a state of some strain following on re-crystallisation and that a few crystals grew in consequence. This case is very similar to that in which large crystals are produced by slight straining followed by heat and it seems probable that the cause and method of growth are the same.

3. The relations observed between crystal size and temperature for the same degree of deformation are the reverse of what is usual. In cases where

there is no doubt that re-crystallisation has taken place, the higher the temperature of heating the larger are the new crystals.* On the other hand the single crystals produced by the authors are formed at the lowest temperatures at which growth occurs and if the temperature is raised the crystals become smaller for the same degree of deformation. This was shown quite conclusively in their previous paper.† The raising of the temperature is equivalent to increasing the deformation and the smaller crystal size is due in both cases to growth starting from a larger number of centres. Moreover, unlike the crystals ordinarily produced by re-crystallisation, these large crystals do not grow at one another's expense. It appears as if the number of centres from which growth starts determines the number of crystals in the final state.

The authors are extending their experiments on the production of single crystals to other metals. They desire to acknowledge the valuable assistance of Mr. H. M. Chapple in carrying out the tensile tests.

Address of the President, Prof. C. S. Sherrington, at the Anniversary Meeting, November 30, 1921.

Since the last Anniversary Meeting the roll of the Society has lost by death fifteen Fellows and one Foreign Member :

Sir William Abney.
Mr. Spencer Pickering.
Dr. A. Muirhead.
Sir Lazarus Fletcher.
Prof. W. Odling.
Prof. L. C. Miall.
Prof. R. B. Clifton.
Lord Moulton.
Prof. A. W. Reinold.
Prof. E. J. Mills.
Colonel J. Herschel.
Mr. G. W. Walker.
Dr. H. Woodward.
The Earl of Ducie.
Dr. F. A. Bainbridge.

On the Foreign List

Prof. G. Lippmann.

The Anniversary Meeting affords appropriate opportunity for some spoken reference to them.

The earliest loss was that of William de Wiveleslie Abney, a Fellow of

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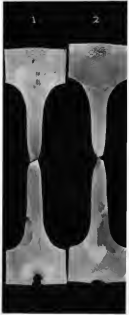
* Mathewson and Phillips, 'Trans. of Amer. Inst. Mining Engineers,' vol. 54, pp. 1–50 (1916).

† *Loc. cit.*, pp 117–119.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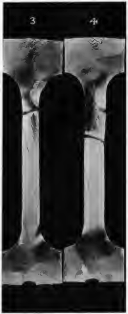
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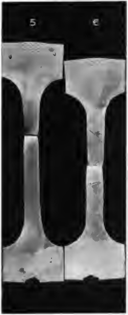
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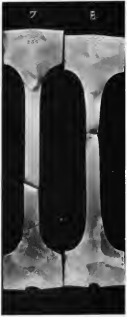
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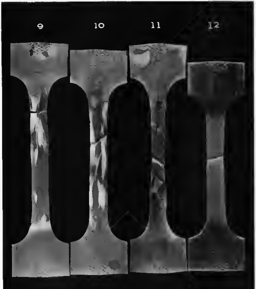
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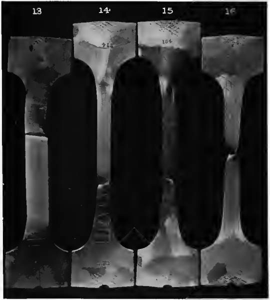
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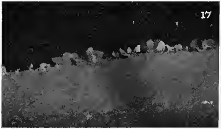

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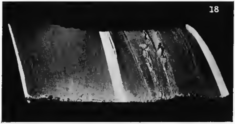

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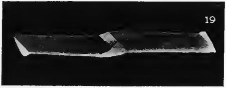

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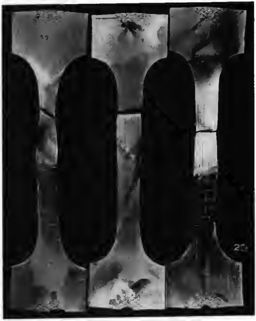

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